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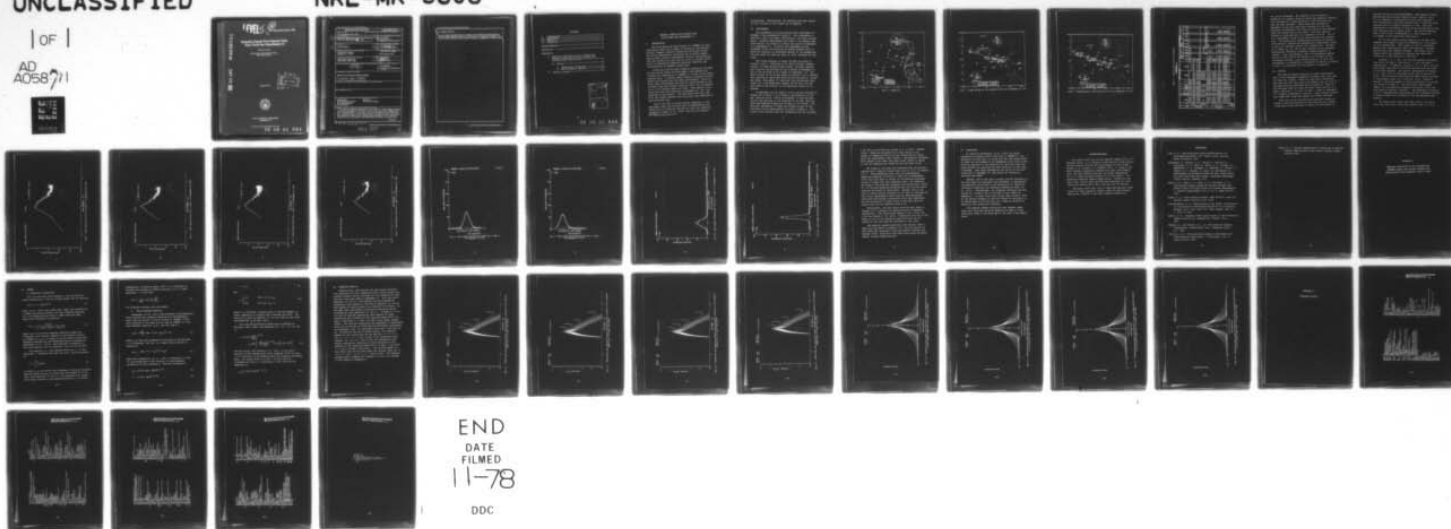
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## Remotely Sensed Wave Spectra From Joint North Sea Experiments II

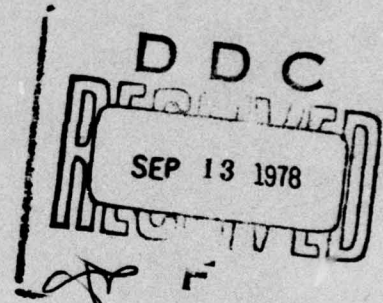
DAVIDSON T. CHEN

*Advanced Space Sensing Application Branch  
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The amount of available remotely sensed wave data, obtained by a Helium-Neon laser profilometer in Joint North Sea Experiment II (JONSWAP II), has been quite limited because the signal emitted from the laser profilometer, to say the least, was very noisy throughout the whole airborne experiment. Fortunately, among the very few flights whose data was relatively less noisy, steady offshore wind conditions were found to exist for the single flight on September 19, 1973. Wave spectra calculated from wave data obtained by this particular flight are presented in this report. Due to (Continued)		

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20. Abstract (Continued)

the lack of strong current gradients in the experiment area, the feasibility of inferring currents by using the technique proposed by Huang, et al. (1972) could not be appropriately investigated. However, this particular technique has been included in this report as an Appendix for reference purposes.

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## REMOTELY SENSED WAVE SPECTRA FROM JOINT NORTH SEA EXPERIMENTS II

### I. INTRODUCTION

The Joint North Sea Wave Project II (JONSWAP II) was a cooperative effort by a number of scientists from Germany, Holland, Denmark, England, Canada and the United States. One of the experimental objectives was to obtain remote sensing data, from an instrumented aircraft simultaneously with the ground-truth data from an array of surface instruments for addressing important questions regarding the interpretation of remotely sensed data.

Scientists from the Naval Research Laboratory and NASA Wallops Flight Center utilized NASA's instrumented C-54 aircraft for observation in JONSWAP II, as one of the remote sensing teams. A typical remote sensing instrument carried aboard the aircraft was the laser profilometer. This airborne laser profilometer profiled the ocean surface as the aircraft flew with constant velocity and at the altitude of 91.5 or 152.4 meters above the ocean. Wave spectra calculated from wave data obtained on September 19, 1973, are presented in this report. The data were relatively less noisy and steady offshore wind conditions were observed on that particular day.

Due to the lack of strong current gradients in the experiment area, the original goal of demonstrating the feasibility of inferring currents by using the technique proposed by Huang, et al. (1972) could not be properly

Note: Manuscript submitted June 15, 1978.

investigated. Nevertheless, the technique has been worked out and included in this report as an Appendix.

## II. EXPERIMENTS

The placements of in-situ ground-truth instruments of JONSWAP II are presented in Figure 1. The instruments at Stations 4 and 8 are shown, particularly, for their arrangements. Airborne measurements were made in the general area from Station 4 to Station 11 during the period of September 17 to September 27. Of which, only September 18 and September 19 had the condition of steady offshore wind in which the analysis is interested because of its assumptions, the data taken on these two days is, thus, selected for the study.

The flight patterns of these two days are shown in Figures 2 and 3. According to Dr. Walsh (private communication), of NASA Wallops Flight Center, the NASA airplane was flying at the altitude of 152.4 meters on September 18 and at the altitude of 91.5 meters on September 19. The small circles on the flight paths in Figures 2 and 3 indicate the locations at which data from Inertial Navigation System was taken. The symbol "P" indicates that photographs were taken with 70 mm Hasselbold cameras (80 mm lens) out the left side of the aircraft at the depression angles of 45 degrees.

On September 18 over Station 8 the wind was recorded as steady for 14 hours at 13.5 M/sec in the direction of 121 deg. from the north. While on September 19 over the same station the wind was in the direction of 147 deg. from the north and remained steady for 12 hours at 12.5 M/sec. The detailed information on these two flights as well as the available in-situ measurements is listed in Table 1. The dotted lines indicate that the information was not recorded

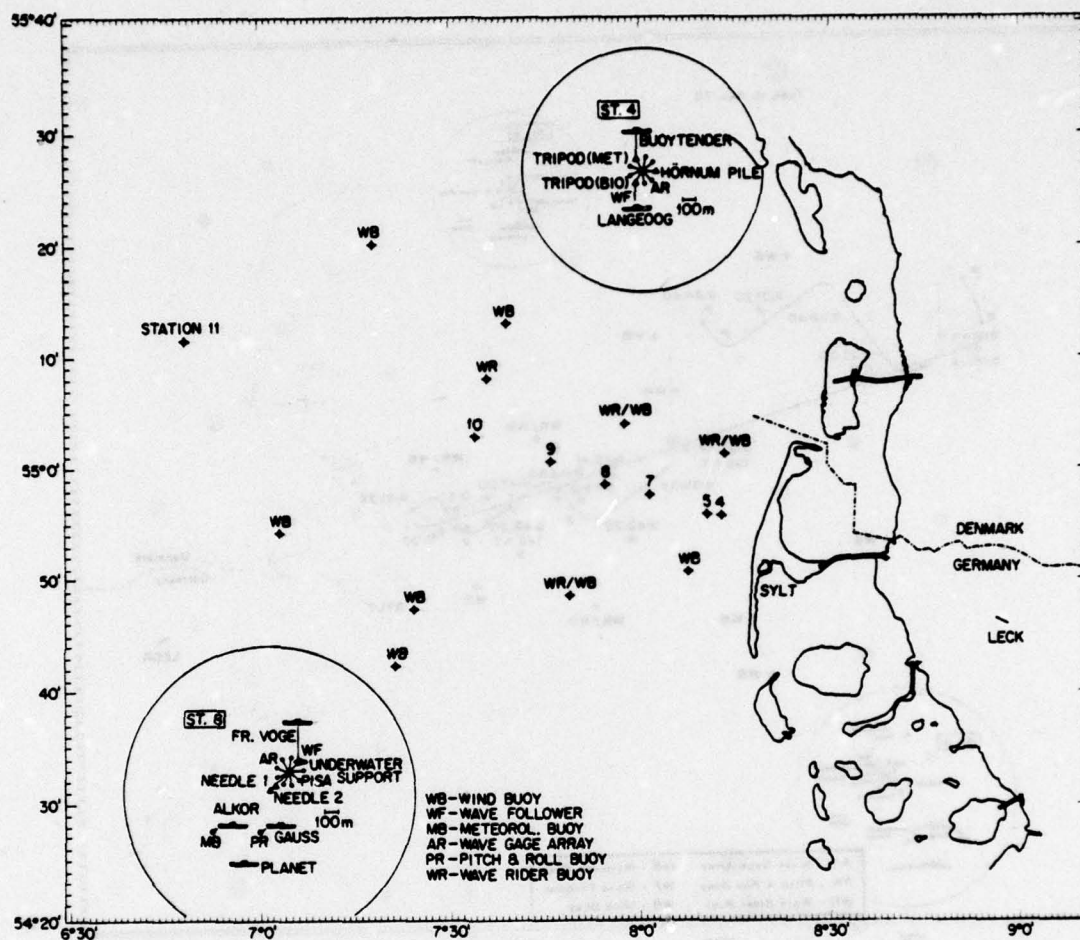


Fig. 1 - Jonswap II

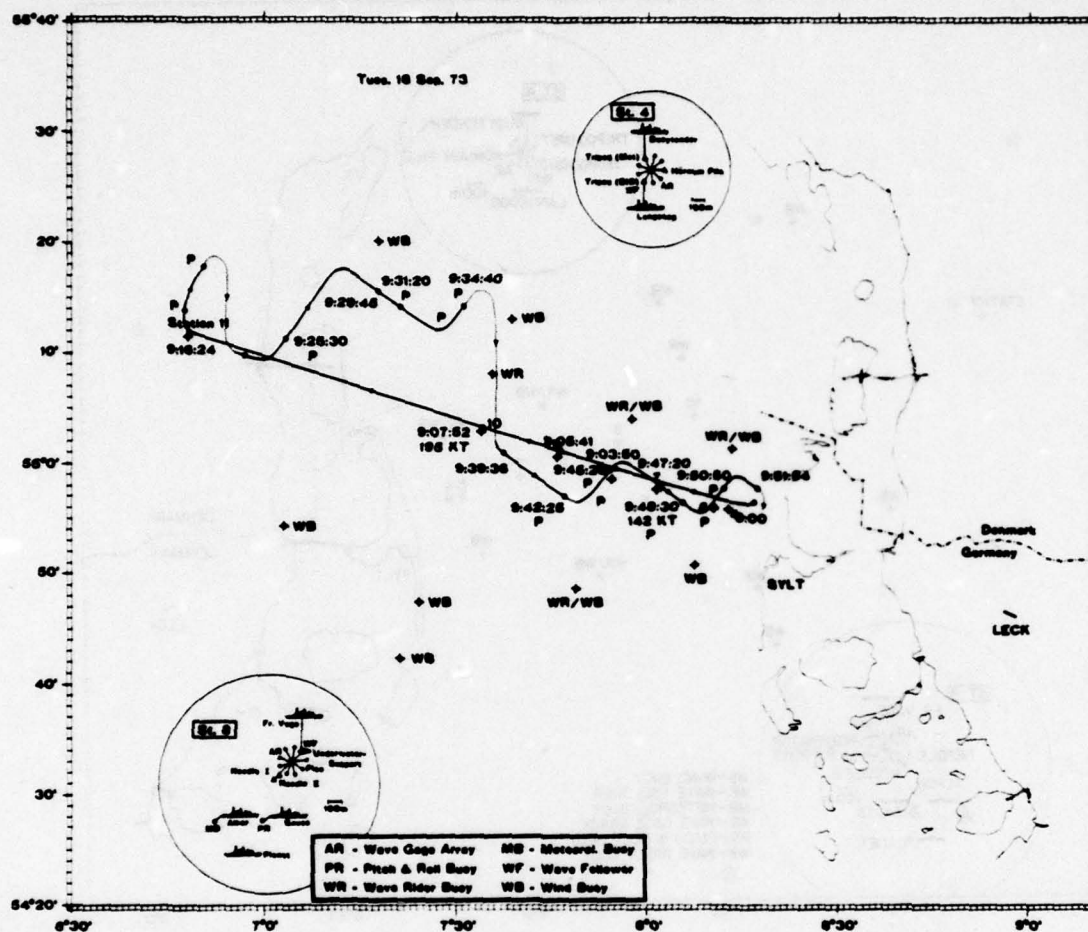


Fig. 2 - Flight pattern at the altitude of 152.4 M on September 18, 1973

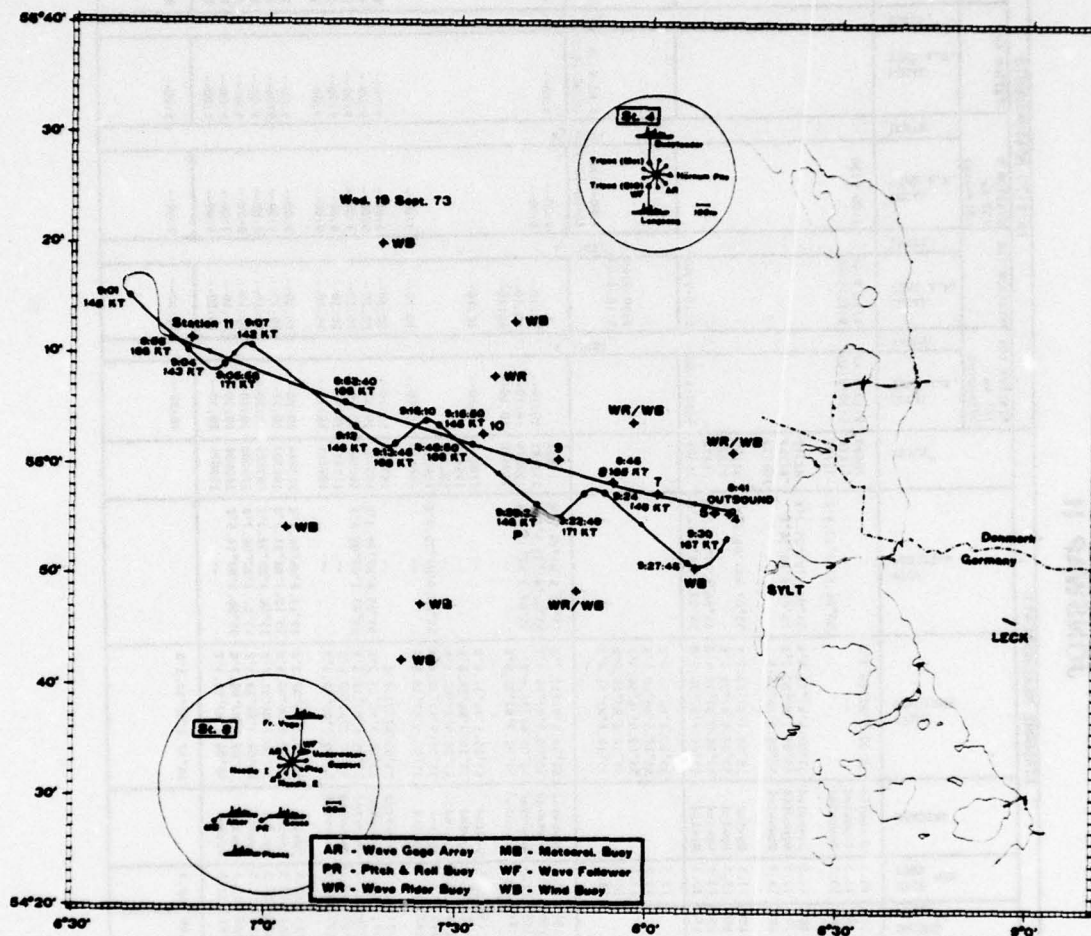


Fig. 3 - Flight pattern at the altitude of 91.5 M on September 19, 1973

Table 1 - Airborne and In-Situ Instruments

JONSWAP II

AIRBORNE MEASUREMENTS											IN-SITU MEASUREMENTS										
DATE	INST.	LOCAL TIME A.M.	TAPE NO.	FILE NO.	ALTITUDE	GROUND SPEED	WIND COND. & WIND	READING	START POSITION	STOP POSITION	PRECIP.	STATION 100 (65 km offshore)		STATION 9 (37 km offshore)		STATION 80		STATION 60			
												LOCAL TIME A.M.	INST.	LOCAL TIME A.M.	INST.	LOCAL TIME A.M.	INST.	LOCAL TIME A.M.	INST.		
Tuesday, Sept. 18, 1973 9:00 AM-10:30 AM	Laser & Monocoord Radar	9:01:30-9:04:30	1	3	152.4	189	13.5	Downwind	55°02.5'N 74°40.1'E	--	5098	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	
		9:04:30-9:07:30	1	4	152.4	189	13.5	Downwind	--	--	6116	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	
		9:07:30-9:10:30	2	6	609.6	204	13.5	Downwind	55°07.4'N 74°14.5'E	55°06.8'N 73°13.9'E	71734	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	
		9:10:30-9:13:30	2	7	609.6	202	13.5	Downwind	55°08.7'N 75°05.2'E	55°08.7'N 75°05.2'E	82352	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	
		9:13:30-9:16:30	3	8	3352.8	180	13.5	Upwind	55°09.1'N 77°00.2'E	55°07.4'N 77°00.1'E	97292	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	
		9:16:30-9:19:30	3	9	3352.8	180	13.5	Upwind	55°07.0'N 77°09.1'E	55°04.7'N 77°26.7'E	91736	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	
		9:19:30-9:22:30	3	10	3352.8	181	13.5	Upwind	55°07.0'N 77°16.1'E	55°04.7'N 77°26.7'E	71737	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	
		9:22:30-9:25:30	3	11	3352.8	182	13.5	Upwind	55°04.7'N 77°28.7'E	55°02.3'N 77°32.2'E	66178	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	
		9:25:30-9:28:30	3	12	152.4	189	13.5	Upwind	55°13.0'N 76°42.0'E	55°02.3'N 77°32.2'E	96301	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	
		9:28:30-9:31:30	3	13	152.4	189	13.5	Downwind	55°17.5'N 76°49.7'E	--	71738	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	
		9:31:30-9:34:30	3	14	152.4	189	13.5	Downwind	55°14.8'N 77°31.4'E	--	71739	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	9:10-9:14	
Wednesday, Sept. 19, 1973 8:40 AM-10:20 AM	Laser & Monocoord Radar	8:44-8:45:30	1	2	91.5	186	12.5	Downwind	54°59.0'N 77°52.7'E	55°00.9'N 77°44.1'E	71858	10:10	10:10	10:10	10:10	10:10	10:10	10:10	10:10	10:10	
		8:45:30-8:47	1	3	91.5	186	12.5	Downwind	55°00.9'N 77°44.1'E	55°02'N 77°35.6'E	152681	10:10	10:10	10:10	10:10	10:10	10:10	10:10	10:10	10:10	
		8:47-8:48:30	1	4	91.5	185	12.5	Downwind	55°02'N 77°35.6'E	55°02.7'N 77°31.8'E	155074	10:10	10:10	10:10	10:10	10:10	10:10	10:10	10:10	10:10	
		8:48:30-8:50	1	5	91.5	187	12.5	Downwind	55°02.7'N 77°31.8'E	--	157420	10:10	10:10	10:10	10:10	10:10	10:10	10:10	10:10	10:10	
		8:50-8:51:30	2	6	91.5	145	12.5	Upwind	55°15.1'N 76°37.4'E	--	218042	10:10	10:10	10:10	10:10	10:10	10:10	10:10	10:10	10:10	
		8:51:30-8:53	2	7	91.5	145	12.5	Upwind	55°10.3'N 76°58.6'E	--	275949	10:10	10:10	10:10	10:10	10:10	10:10	10:10	10:10	10:10	
		8:53-8:54:30	2	8	91.5	145	12.5	Upwind	55°07.9'N 77°04.2'E	--	164705	10:10	10:10	10:10	10:10	10:10	10:10	10:10	10:10	10:10	
		8:54:30-8:56	2	9	91.5	145	12.5	Upwind	55°02.9'N 77°30.4'E	55°00.4'N 77°35.9'E	154333	10:10	10:10	10:10	10:10	10:10	10:10	10:10	10:10	10:10	
		8:56-8:57:30	2	10	91.5	142	12.5	Upwind	55°00.4'N 77°35.9'E	--	148530	10:10	10:10	10:10	10:10	10:10	10:10	10:10	10:10	10:10	
		8:57:30-9:00:30	3	11	3505.2	193	12.5	Downwind	55°03'N 77°33.9'E	--	157543	10:10	10:10	10:10	10:10	10:10	10:10	10:10	10:10	10:10	
		9:00:30-9:03:30	3	12	3505.2	193	12.5	Downwind	55°04.3'N 77°25.2'E	--	157543	10:10	10:10	10:10	10:10	10:10	10:10	10:10	10:10	10:10	

but can be estimated. The heading of the airplane is presented in a general sense of upwind and downwind, however, this information is used precisely in the calculation as what has been recorded. Three tapes were recorded on September 18 and four tapes were recorded the next day. Excluding calibrations, the files with data of real measurements are listed also in the table. Each file takes 91 seconds of digitized data at a frequency of 90 Hz. The in-situ instruments listed in the table provide wave information. The Institute of Oceanographic Sciences at Wormley, Great Britain, operated the Telemetering Accelerometer Buoys  $A_1$  and  $A_2$  at Stations 10W and 10E, respectively. The Wave Rider Buoys,  $W_4$ ,  $W_5$ , and  $W_6$  were operated by the Deutsches Hydrographic Institute at Hamburg, Federal Republic of Germany. Very unfortunately, due to circumstances beyond control at the time of the flights, all of these in-situ instruments provide a very limited quantity of data. As a consequence, no ground-truth information on waves at Stations 10 and 11 is available for the purpose of comparison.

### III. RESULTS

The Spectra-Physics Geodolite 3A Laser Profilometer used in this experiment happened to produce very noisy data for these two flights. There are also clear indications from the data that this laser profilometer lost its lock on the phase shifting mechanism quite frequently. Among all the available data for these two days, data from File 4 of Tape 1 and Files 1, 2, and 3 of Tape 2, taken on September 19, is barely acceptable in quality. After careful examination these four files were chosen for further analyses.

Each file of data contains 8192 digitized numerical values at the time interval of one-ninetieth of a second. A high pass filter was used to filter out the effects of

aircraft motions on the measurements. The numerical filter applied was the so-called "Martin Filter" (Martin, 1957). It is a symmetric, non-recursive filter which features a sine termination to the gain function and a correction which insures unity at a cutoff frequency of zero. The sine termination is introduced to avoid large oscillations in the gain function due to a sharp cutoff. The cutoff frequency used in the filter corresponded to a cutoff period of 10 seconds in this particular application.

Due to the limited storage capacity of the CDC 1604 computer this amount of data was segmented at a time length of 5.69 seconds each. This length in time is considered adequate for obtaining the ocean wave spectrum. Fifteen spectra were then ensemble averaged. The effects due to Doppler shift were removed by assuming that waves were travelling in the direction of the wind.

Figures 4, 5, 6, and 7 are the wave spectra calculated from File 4 of Tape 1, and Files 1, 2, and 3 of Tape 2, respectively. In addition, Figures 8, 9, 10, and 11 are the wave height distribution functions obtained from the files in the same sequence. The vertical coordinates of Figures 4, 5, 6 and 7 are in logarithmic scale and in the unit of  $M^2/Hz$ . The horizontal coordinates of these figures are also in logarithmic scale, but in the unit of Hz. Figures 4 through 7 show wind speeds in M/sec and fetches in M as well as Figures 8 through 11. The significant wave heights (SWH's) in M as defined by Neumann and Pierson (1966) are also shown in Figures 4 through 7. The abscissas, of Figure 8 to 11, represent wave amplitudes and are nondimensionalized by being divided with variances of the corresponding wave spectra.

The laser noise levels vary from 0.048 M to 0.094 M while the laser noise limits are greater than 3.47, 4.26,

JONSWAP 2 WIND=12.5 FETCH=155074

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□ - LASER (SWH = 1.62 M )

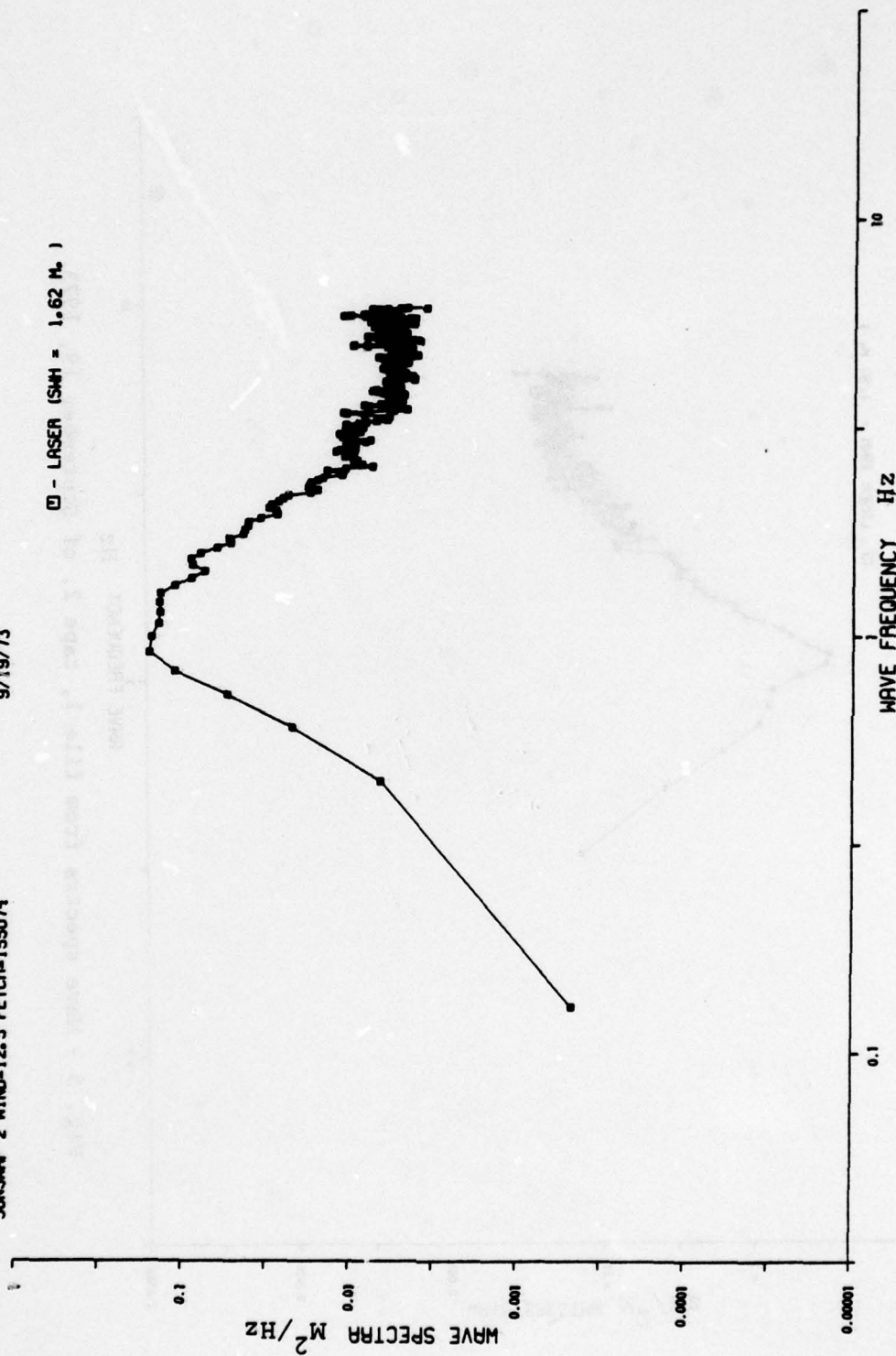


Fig. 4 - Wave spectra from file 4, tape 1, of September '19, 1973

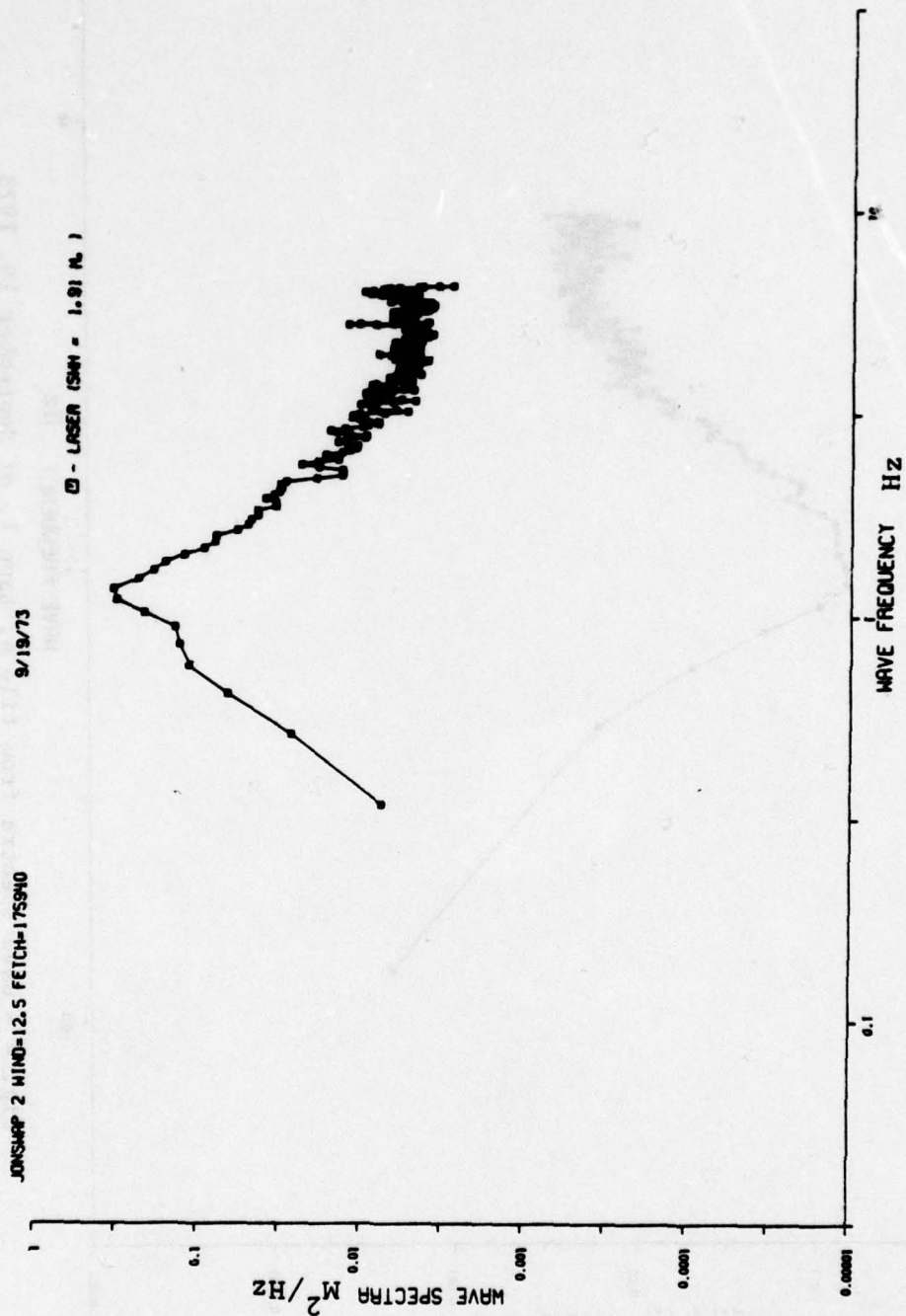


Fig. 5 - Wave spectra from file 1, tape 2, of September 19, 1973

JONSWAP 2 WIND-12.5 FETCH-164705

9/19/73

□ - LASER (SWH = 2.00 M )

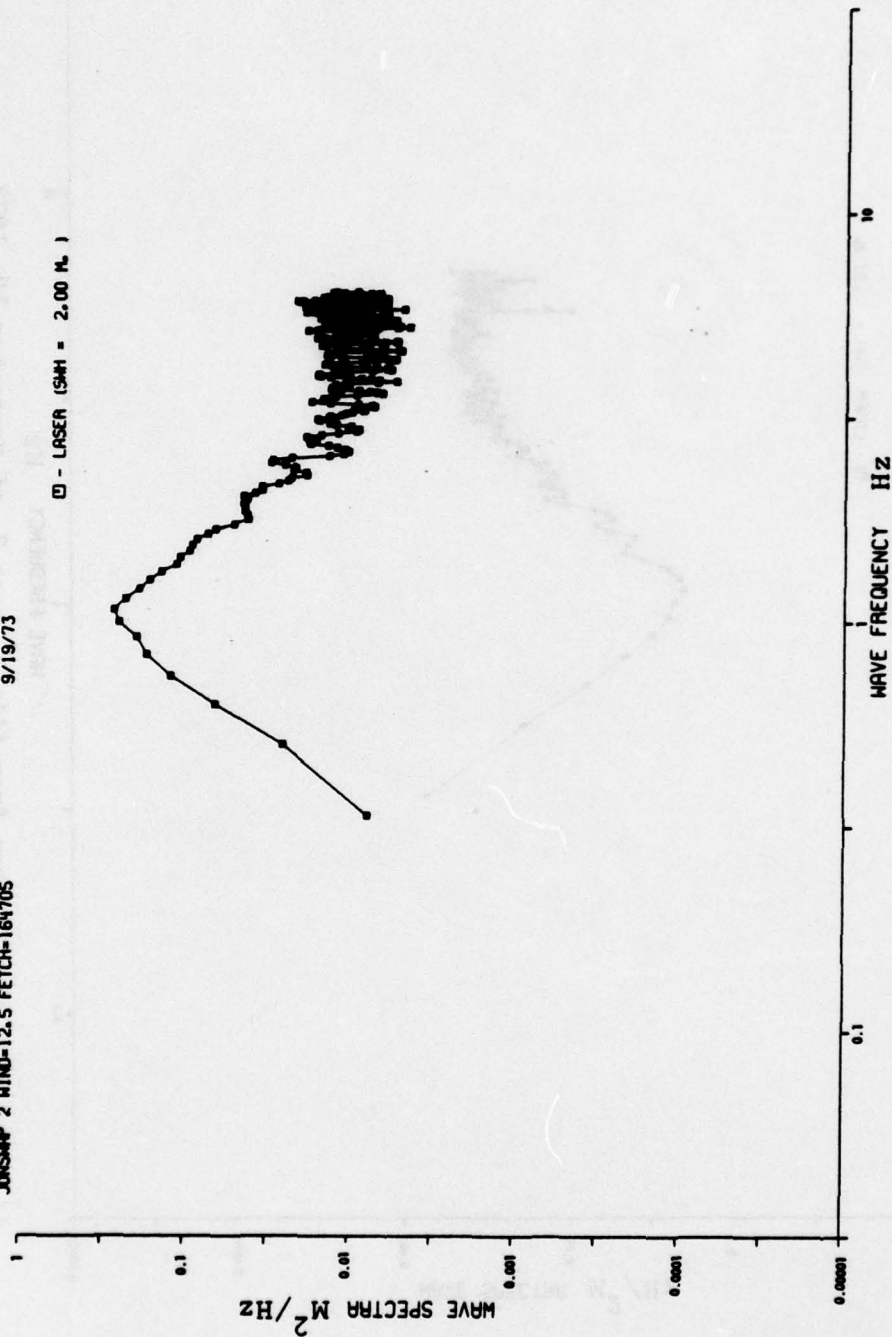


Fig. 6 - Wave spectra from file 2, tape 2, of September 19, 1973

JONSWAP 2 WIND=12.5 FETCH=154333

9/19/73

□ - LASER (SMH = .91 M.)

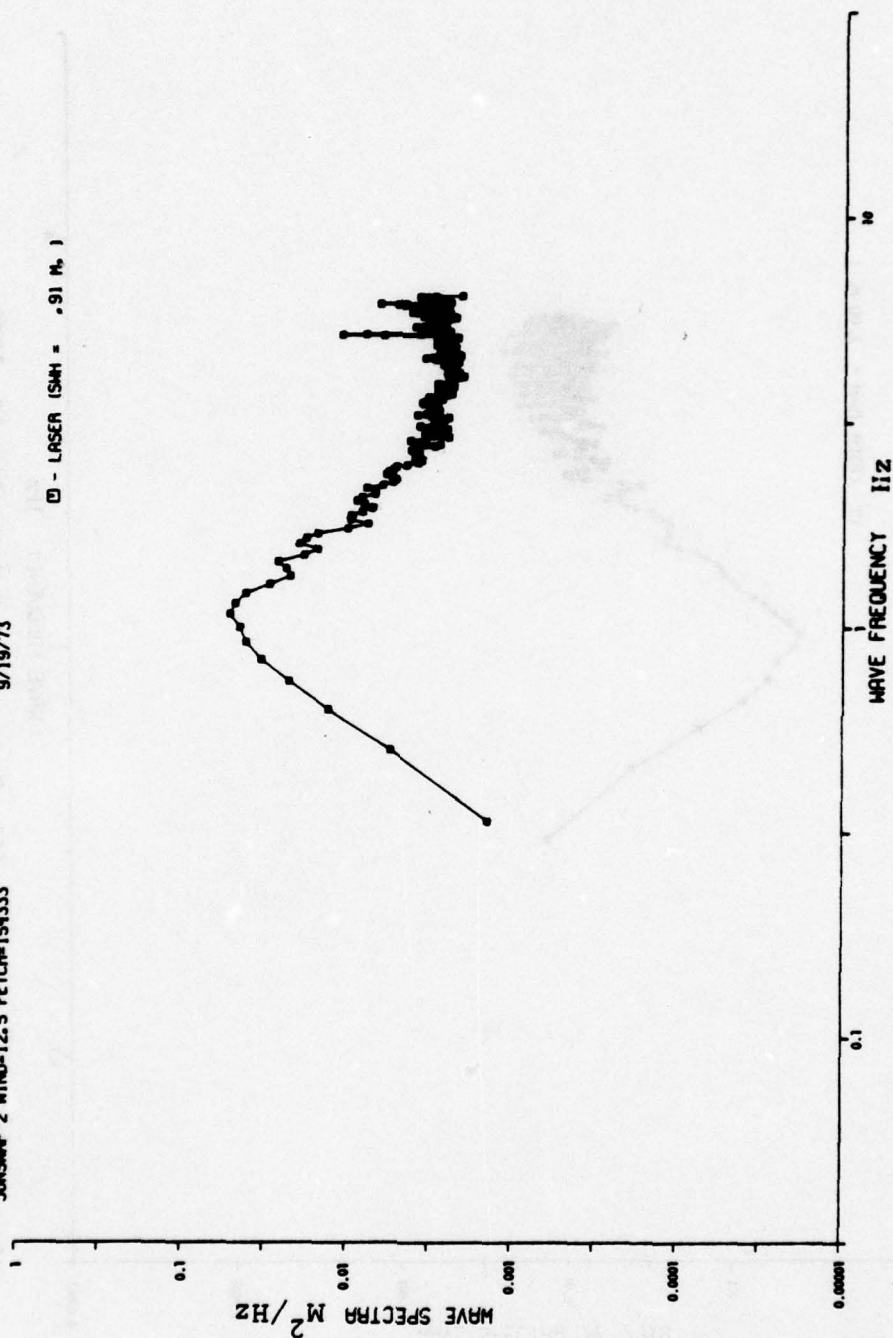


Fig. 7 - Wave spectra from file 3, tape 2, of September 19, 1973

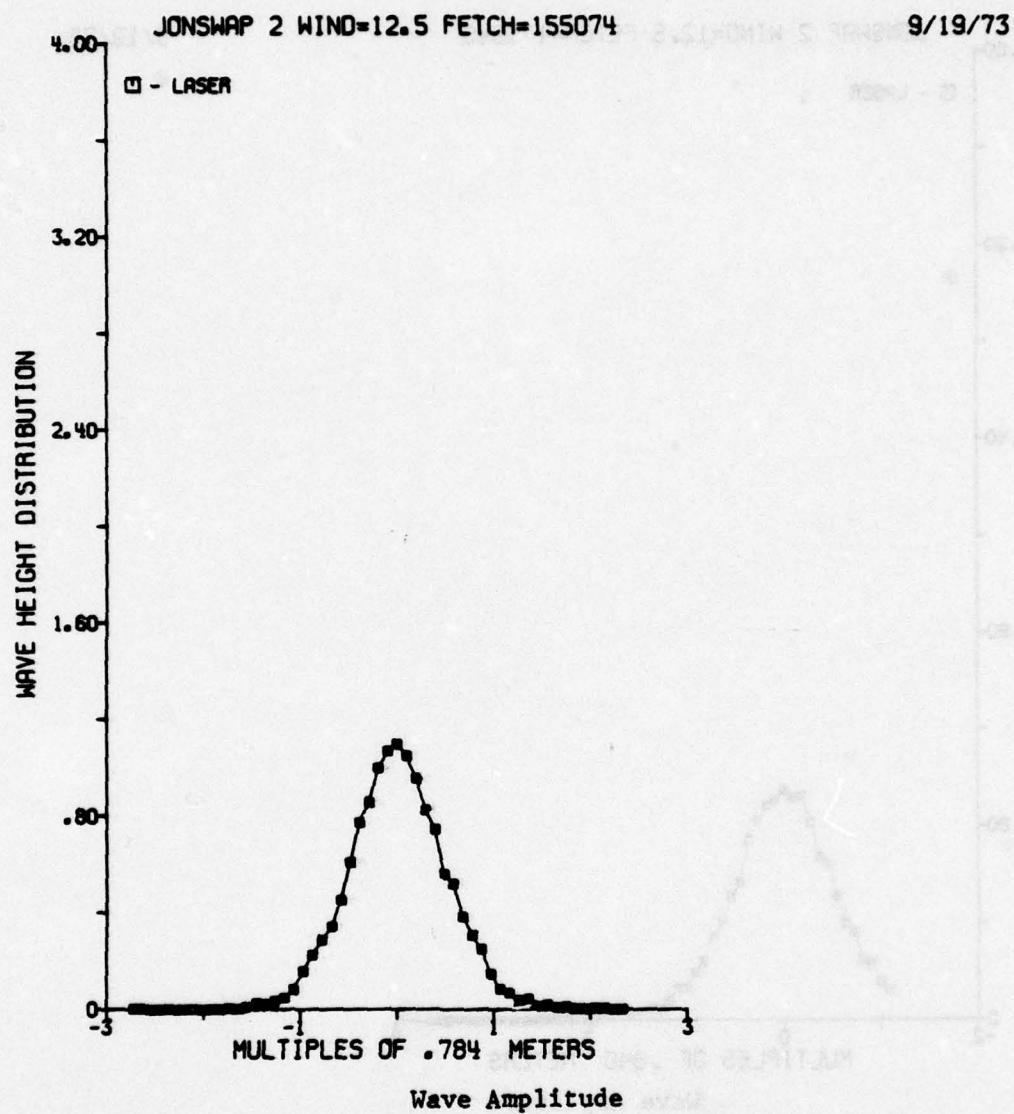


Fig. 8 - Wave height distributions from file 4, tape 1,  
of September 19, 1973

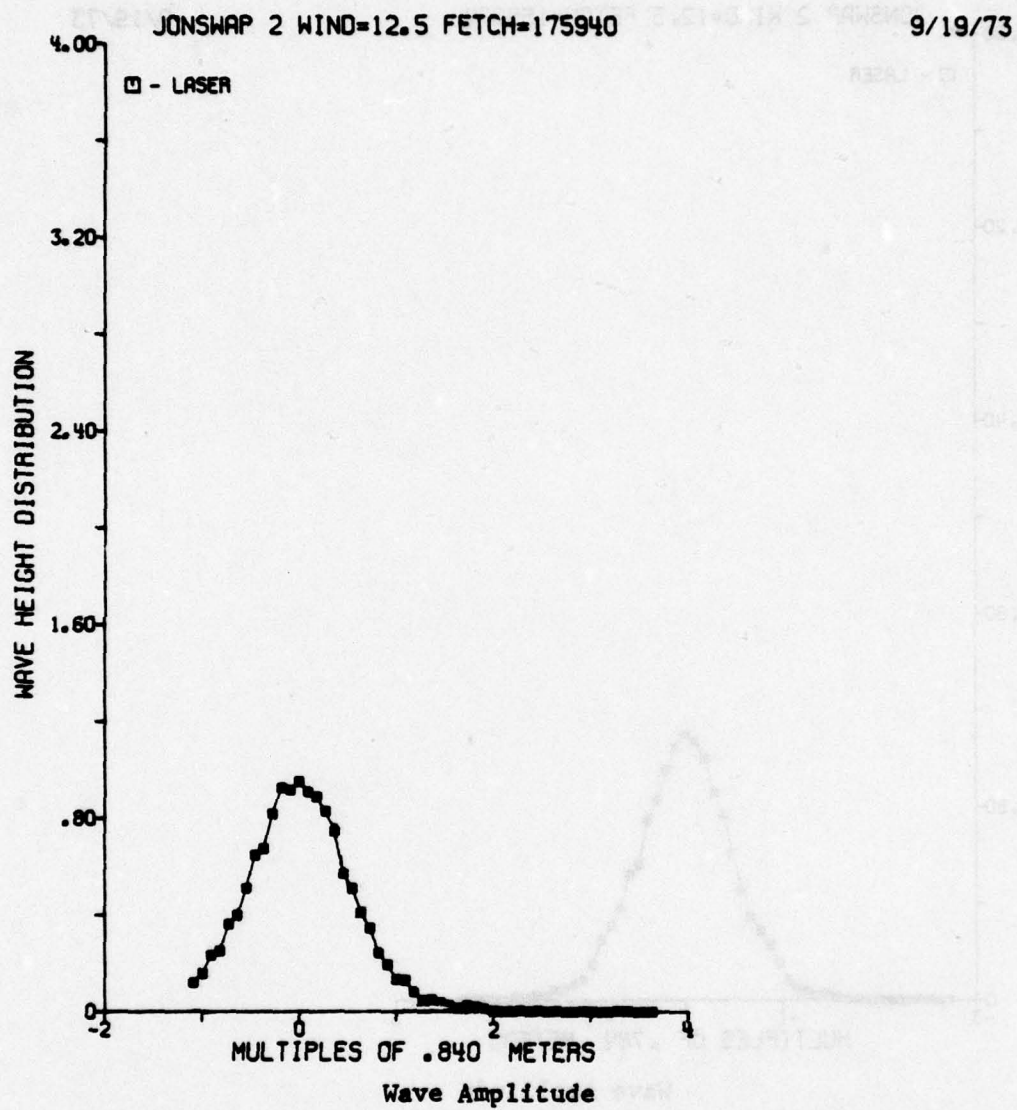


Fig. 9 - Wave height distributions from file 1, tape 2,  
of September 19, 1973

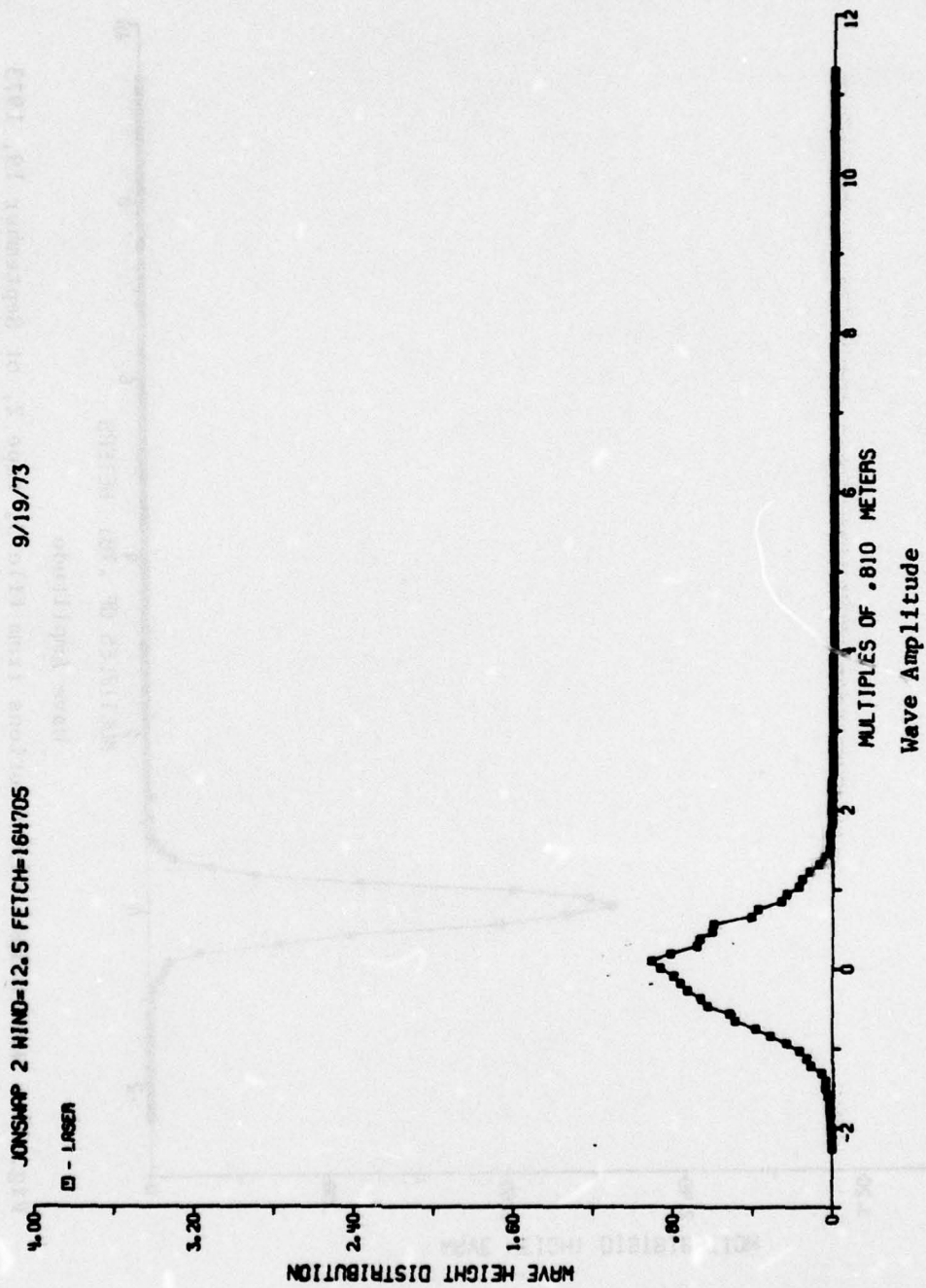


Fig. 10 - Wave height distributions from file 2, tape 2, of September 19, 1973

JONSHAP 2 WIND=12.5 FETCH=154333

9/19/73

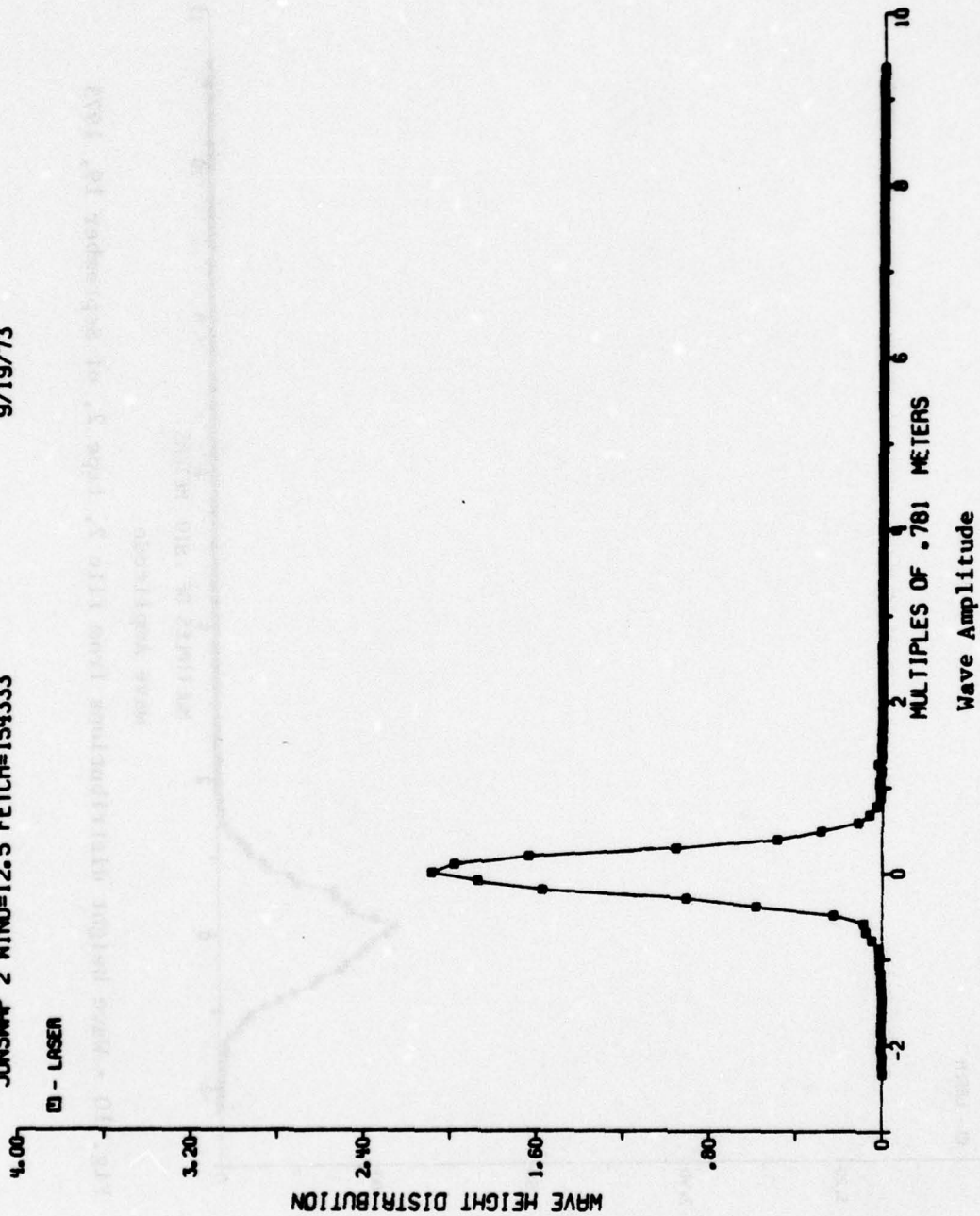


Fig. 11 - Wave height distributions from file 3, tape 2, of September 19, 1973

3.36, and 4.02 Hz shown by Figures 4, 5, 6, and 7, respectively. These are unusually high noise levels at low ranges of frequencies which are the indications of highly noisy and undesirable laser signals. The spectral estimates which appear to be lower than laser noise levels in values at the low frequency are caused by the high pass filter.

The slopes at the high wave frequency ends of the wave spectra show a range of values from -3.25 to -4.71 in Figures 4 to 7. Some mechanisms other than the wave-breaking mechanism suggested by Phillips (1958) and Kitaigorodskii (1961) must have been in control of the physical processes as well at these high wave frequency ends. For otherwise the slope at the high wave frequency end should show a value of 5 if the wave-breaking mechanism were the only one which controls the growth of these waves. However, due to the lack of strong current gradients in the area as indicated by the in-situ measurements there might be some mechanisms other than wave-current interaction which were responsible for the variations of slope values at the high wave frequency ends from the expected value of -5.

Nevertheless, the wave height distributions shown in Figures 8 to 11 display the characteristics of Gaussian distribution. The values shown beyond 2.1 M, 2.03 M, and 1.95 M in Figures 9, 10, and 11, respectively are due to the drops of bits in the recording tapes which are not the results of the real physical processes in the ocean.

The remotely sensed significant wave heights (SWH's), which are also shown in Figures 4 to 7 and are defined as four times the variances of the wave spectra (Neumann and Pierson, 1966), agree well with those from visual estimates (Walsh, private communications).

#### IV. CONCLUSION

As stated by Hasselmann, et al. (1973) for waves generated by offshore wind at the site of JONSWAP II, the assumption of deep water is valid only for wind speeds below 25 M/sec and the assumption of homogeneous wave field in the direction parallel to the shoreline is valid only when the angle between the shoreline and wind direction is less than 30 degrees. Both these assumptions are valid for the wind conditions on September 19, upon which the theoretical analyses were based.

However, due to the lack of strong current gradients in the area where the experiment was performed, no appropriate investigation can be done on the feasibility of inferring currents by employing the technique proposed by Huang, et al. (1972). Nevertheless, this proposed technique has been worked out in detail and is included in this report as Appendix A. An area, with known strong shear current, such as the western boundary of the Gulf Stream is desirable to be established as the test site for inferring currents by employing this particular technique.

The remotely sensed significant wave heights (SWHs) agree well with what would be expected for SWHs at those particular areas in the North Sea at the time of the experiments.

#### ACKNOWLEDGEMENTS

The author would like to give special thanks to Mr. J. T. McGoogan and Mr. H. R. Stanley of NASA Wallops Flight Center, Wallops Island, Virginia for encouragement in this study. Messrs. E. A. Uliana, D. L. Hammond, and K. J. Craig of the Naval Research Laboratory recorded the laser profilometer data, and their efforts and help are highly appreciated. Dr. E. J. Walsh provided Figures 1-3 of this report. His generosity deserves special appreciation. Thanks are also due to Mrs. Carolyn Eden and Miss Marie Spangler for their typing and editing and to Mrs. Jean Ware for her drawing.

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APPENDIX A

NUMERICAL EVALUATION OF THE INTERACTIONS  
BETWEEN STEADY NON-UNIFORM CURRENTS AND  
FETCH-LIMITED WIND-GENERATED GRAVITY WAVES

## A1. THEORY

### a. Theoretical Background

Let  $n$  be the total wave frequency,  $g$  be the gravitational acceleration,  $U$  be the current speed, and the function

$$R(n) = (1 + 4Un/g)^{1/2} . \quad (1)$$

Huang, et al. (1972) have shown that, under the influence of a steady non-uniform current, the wave frequency spectrum,  $\phi(n)$ , for random gravity waves in deep water and under steady wind conditions is given by

$$\phi(n) = \frac{4\phi_0(n)}{[1 + R(n)] [R(n) + (R(n))^2]} \quad (2)$$

where  $\phi_0(n)$  is the wave frequency spectrum without the influence of the current. Because of the special locality of JONSWAP II,  $\phi_0(n)$  is chosen to be the fetch-limited wave frequency spectrum for wind-generated waves as proposed by Hasselmann, et al. (1973). More detailed information on this wave spectrum will be presented later in this section.

From Equation (2), the standard deviation,  $\sigma$ , of wave amplitude,  $\eta$ , measured from mean sea level, can be evaluated as

$$\sigma^2 = \int_0^{n_c} \phi(n) dn \quad (3)$$

in which  $n_c$  is the cutoff wave frequency of the wave frequency spectrum taken as that of a wave with wave length of 30 cm. Thus, from Equations (2) and (3), the influence of a steady non-uniform current on the standard deviation,  $\sigma$ , is known.

Subsequently, as done by Huang (1974), it is possible to evaluate the probability density function,  $p(\eta)$ , of wave amplitude,  $\eta$ , of the form

$$p(\eta) = \frac{1}{\sqrt{2\pi}\sigma} \exp \left( -\frac{1}{2} \frac{\eta^2}{\sigma^2} \right), \quad (4)$$

for different currents and wind speeds.

#### b. Wave Frequency Spectrum

Hasselmann, et al. (1973) have proposed a one-dimensional fetch-limited wave frequency spectrum for wind-generated waves from the results of their studies in JONSWAP I which were conducted at the same site as that of JONSWAP II. This wave frequency spectrum,  $\phi_o(n)$ , has the form of

$$\phi_o(n) = \frac{Kg^2}{n^5} \exp [-1.25 (n_m/n)^4] G(n) \quad (5)$$

where  $n_m$  is the wave frequency at the peak of the spectrum,  $K$  is a parameter, and  $G(n)$  is a shape function which is defined as

$$G(n) = \gamma \exp [-(n - n_m)^2 / 2\xi^2 n_m^2] \quad (6)$$

These four parameters,  $n_m$ ,  $K$ ,  $\gamma$  and  $\xi$  in Equations (5) and (6) are determined by the technique of simultaneously optimizing all four parameters. They are evaluated as

$$n_m = 21.99 (g/W) (gF/W^2)^{-0.33}, \quad (7)$$

$$K = 0.4775 (gF/W^2)^{-0.22}, \quad (8)$$

$$\gamma = 3.3$$

(9)

and

$$\xi = \begin{cases} 0.07 & \text{for } n \text{ in } (0, n_m) \\ 0.09 & \text{for } n \text{ in } (n_m, \infty) \end{cases} \quad (10)$$

where  $F$  is the fetch in meters and  $W$  is the wind speed, in m/sec, measured at 10 meters above the mean sea level. The value of  $n_m$  given by Equation (7) is very close to the value calculated for  $n_m$  by Chen (1972).

Let  $\beta$  be the equilibrium coefficient as defined by Phillips (1958), then, from Equations (5), (6), (7), (8) and (9)

$$\beta = 0.4775 \left( \frac{gF}{W^2} \right)^{-0.22} \cdot 3.3 \exp \left\{ - \left[ \frac{nW}{g} \left( \frac{gF}{W^2} \right)^{0.33} - 21.99 \right] / 967.22 \xi^2 \right\} \quad (11)$$

One can notice, from Equation (11), that  $\beta$  is not only a function of the dimensionless fetch parameter  $gF/W^2$  but also it is a function of the dimensionless wave frequency parameter  $nW/g$ . For fixed values of  $W$  and  $F$ , as the value of  $n$  increases the value of  $\beta$  approaches a limit which can be expressed as

$$\lim_{n \rightarrow \infty} \beta = 0.4775 \left( \frac{gF}{W^2} \right)^{-0.22} \quad (11)$$

## A2. NUMERICAL RESULTS

Theoretically, wave spectra and wave height distribution functions for wave interacting with various steady non-uniform currents can be evaluated for the locations at which the four files were taken on September 19. With the use of Equations (2) and (5), wave spectra can be evaluated by considering wave spectra in the form of Equation (5) as the wave spectra of waves without the influence of currents. By the same token wave height distribution functions can be evaluated by using Equations (4) and (5). Figures A-1, A-2, A-3 and A-4 show the theoretical wave spectra of waves interacting with currents at the locations where File 4 of Tape 1, and Files 1, 2, and 3 of Tape 2 were taken, respectively. The vertical coordinates are presented in logarithmic scale and in the unit of  $m^2/Hz$  and the horizontal coordinates are presented, also, in logarithmic scale and in the unit of Hz. As shown on the top of these figures, the currents' speeds for the curves from the top down are -2, -1.5, -1, -0.5, 0, 0.5, 1, 2, 3, and 5 m/sec in an increasing order. Figures A-5, A-6, A-7, and A-8 are the theoretical wave height distribution functions of waves interacting with currents at the locations where File 4 of Tape 1, and Files 1, 2, and 3 of Tape 2 were taken. The current speeds for the curves from the top down along the vertical axes are -2, -1.5, -1, -0.5, 0, 0.5, 1, 2, 3, and 5 m/sec. The computer program used to compute for Figures A-1 to A-8 is included in this report as Appendix B.

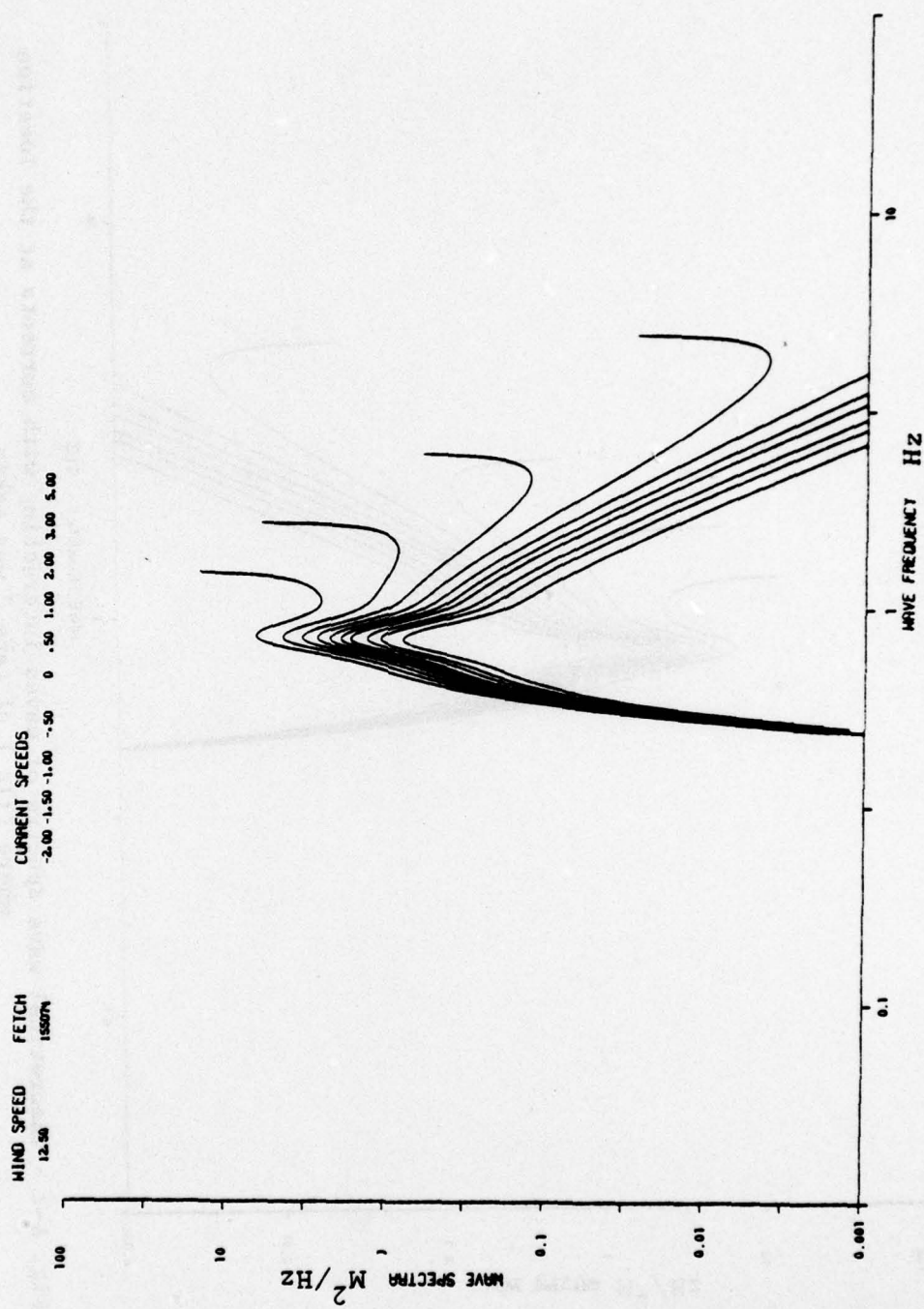


Fig. A-1 - Theoretical wave spectra of waves interacting with currents at the location where file 4 of tape 1 was taken

WIND SPEED      FETCH      CURRENT SPEEDS

12.50      175000      -2.00 -1.50 -1.00 -.50 0 .50 1.00 2.00 3.00 5.00

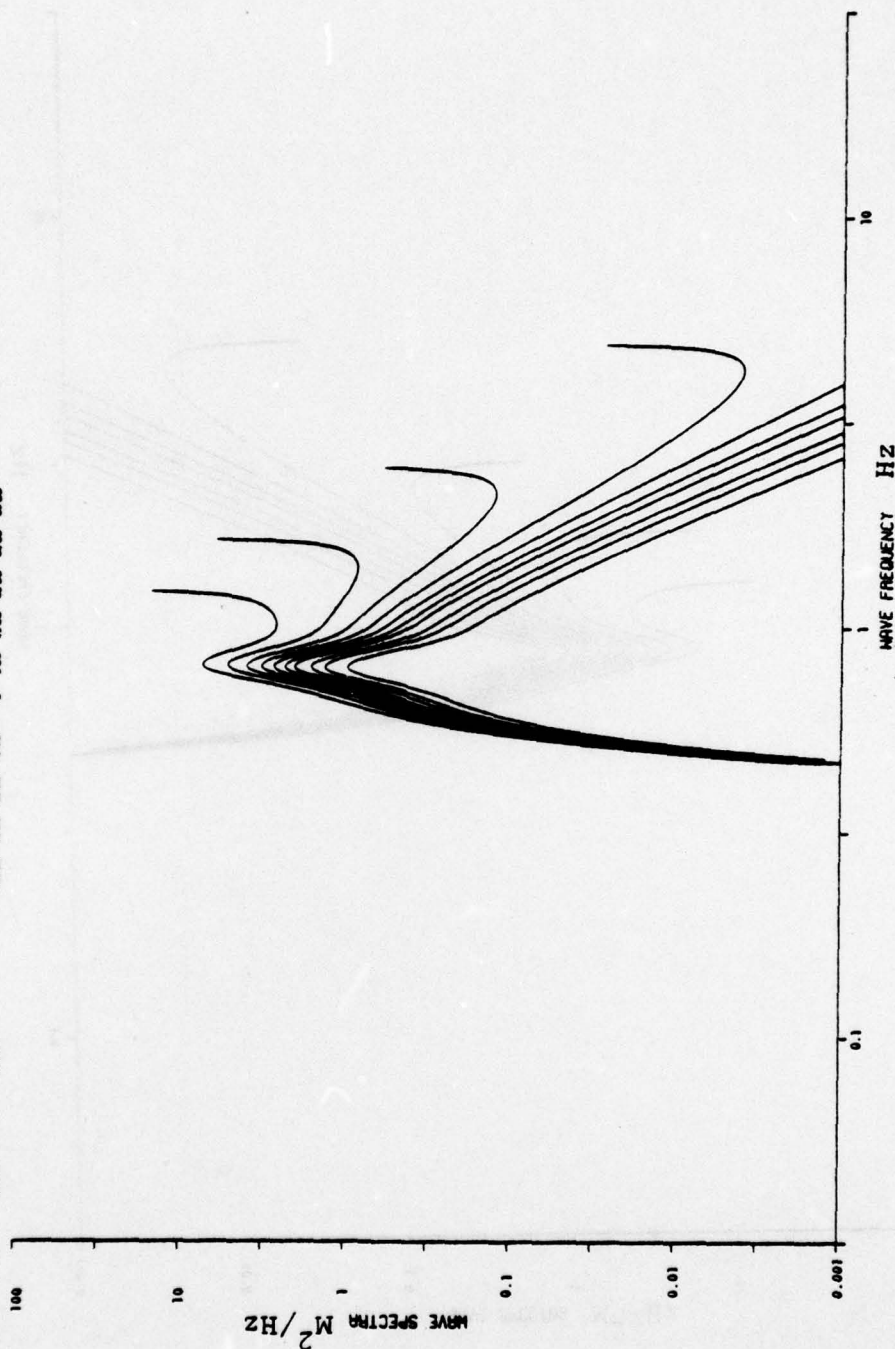


Fig. A-2 - Theoretical wave spectra of waves interacting with currents at the location where file 1 of tape 2 was taken

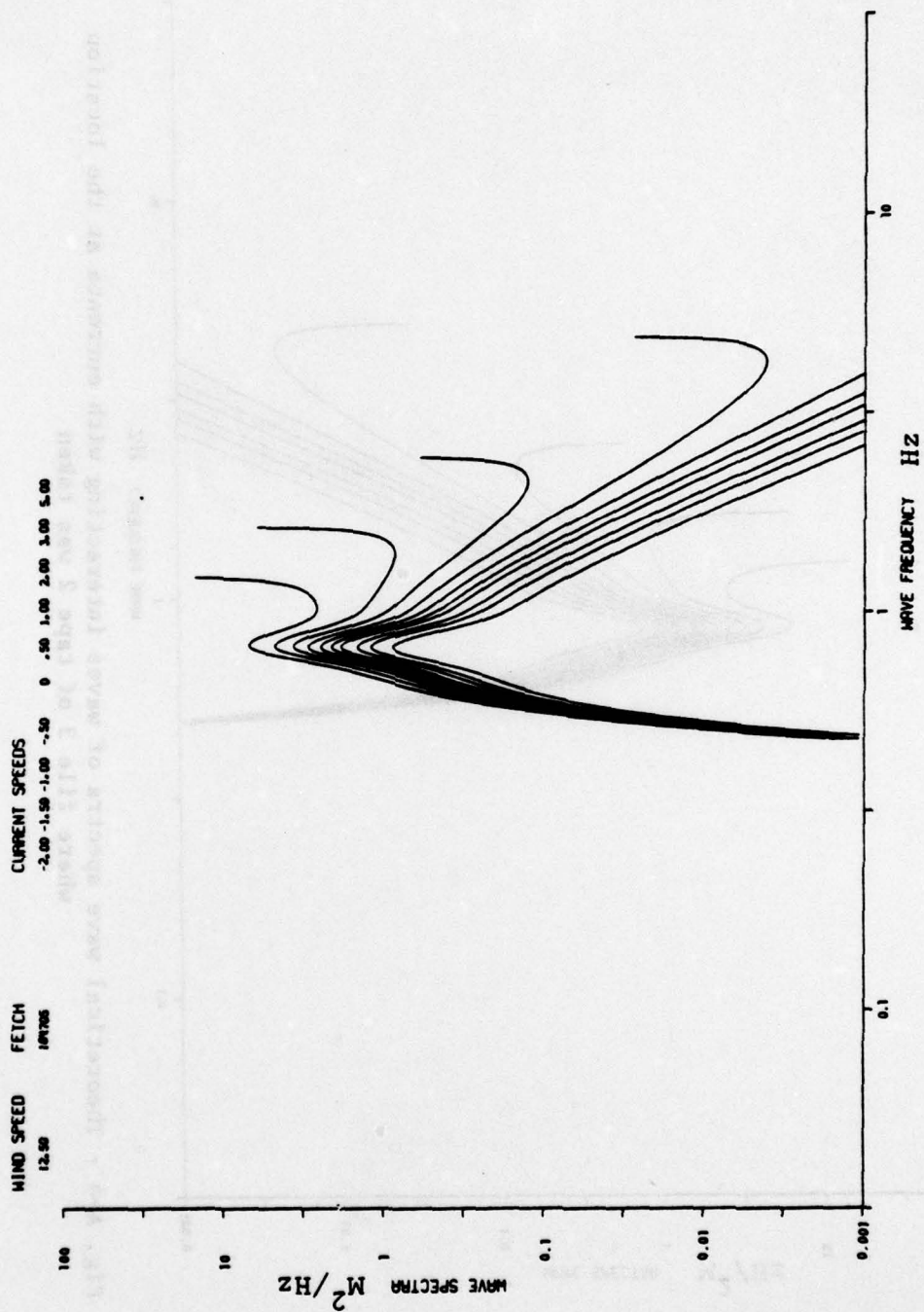


Fig. A-3 - Theoretical wave spectra of waves interacting with currents at the location where file 2 of tape 2 was taken

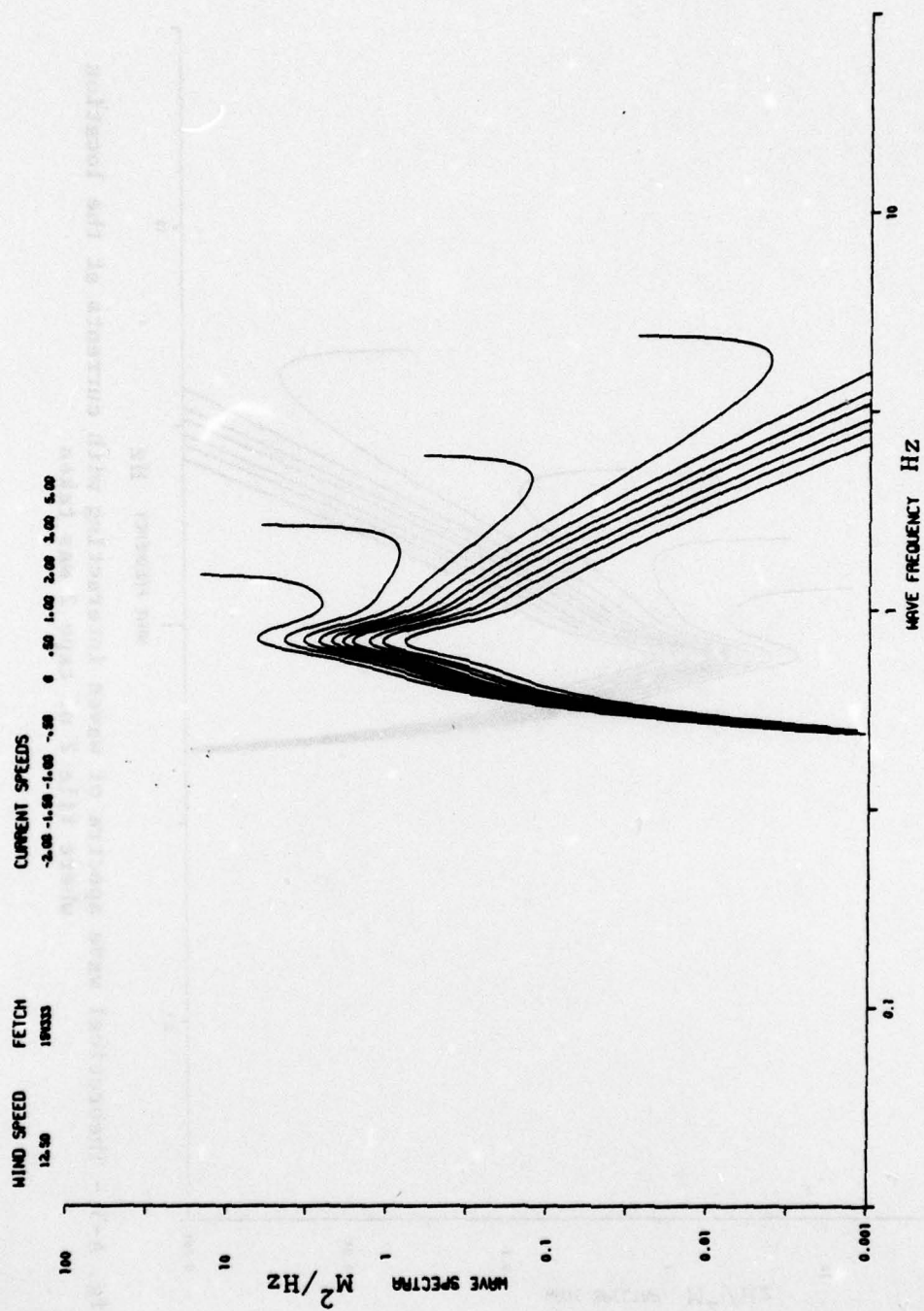


Fig. A-4 - Theoretical wave spectra of waves interacting with currents at the location where file 3 of tape 2 was taken

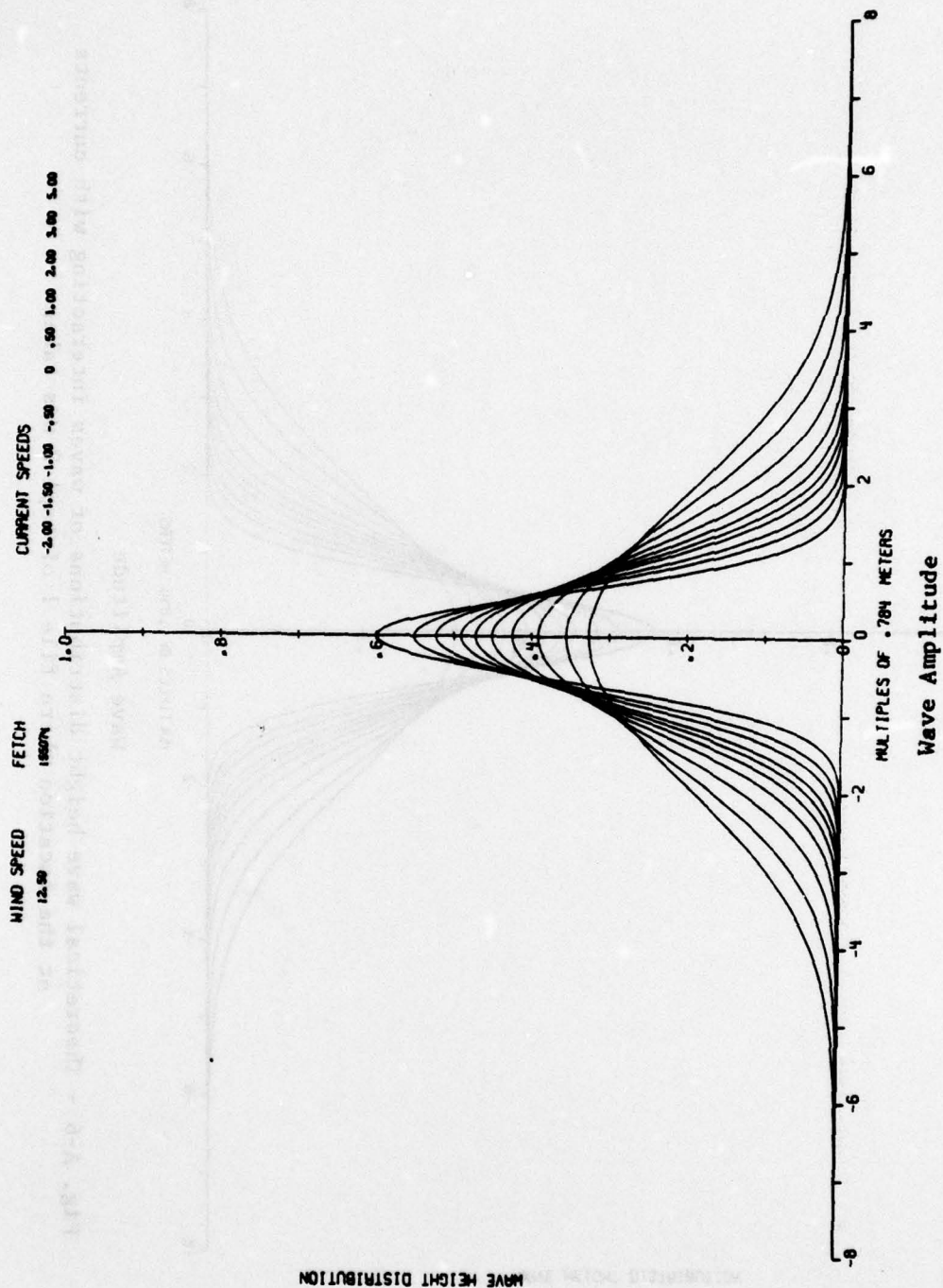


Fig. A-5 - Theoretical wave height distributions of waves interacting with currents at the location where file 4 of tape 1 was taken

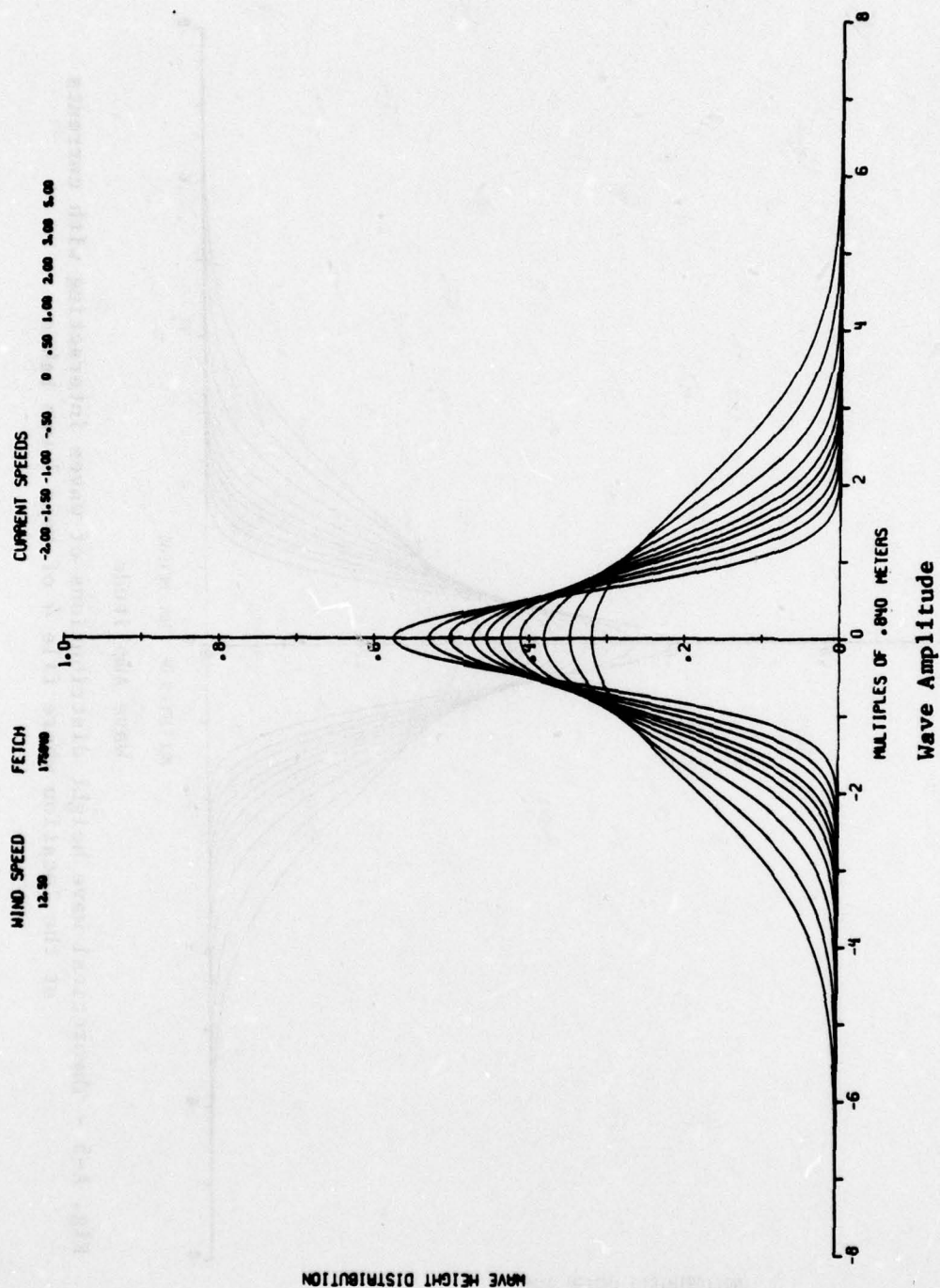


Fig. A-6 - Theoretical wave height distributions of waves interacting with currents at the location where file 1 of tape 2 was taken

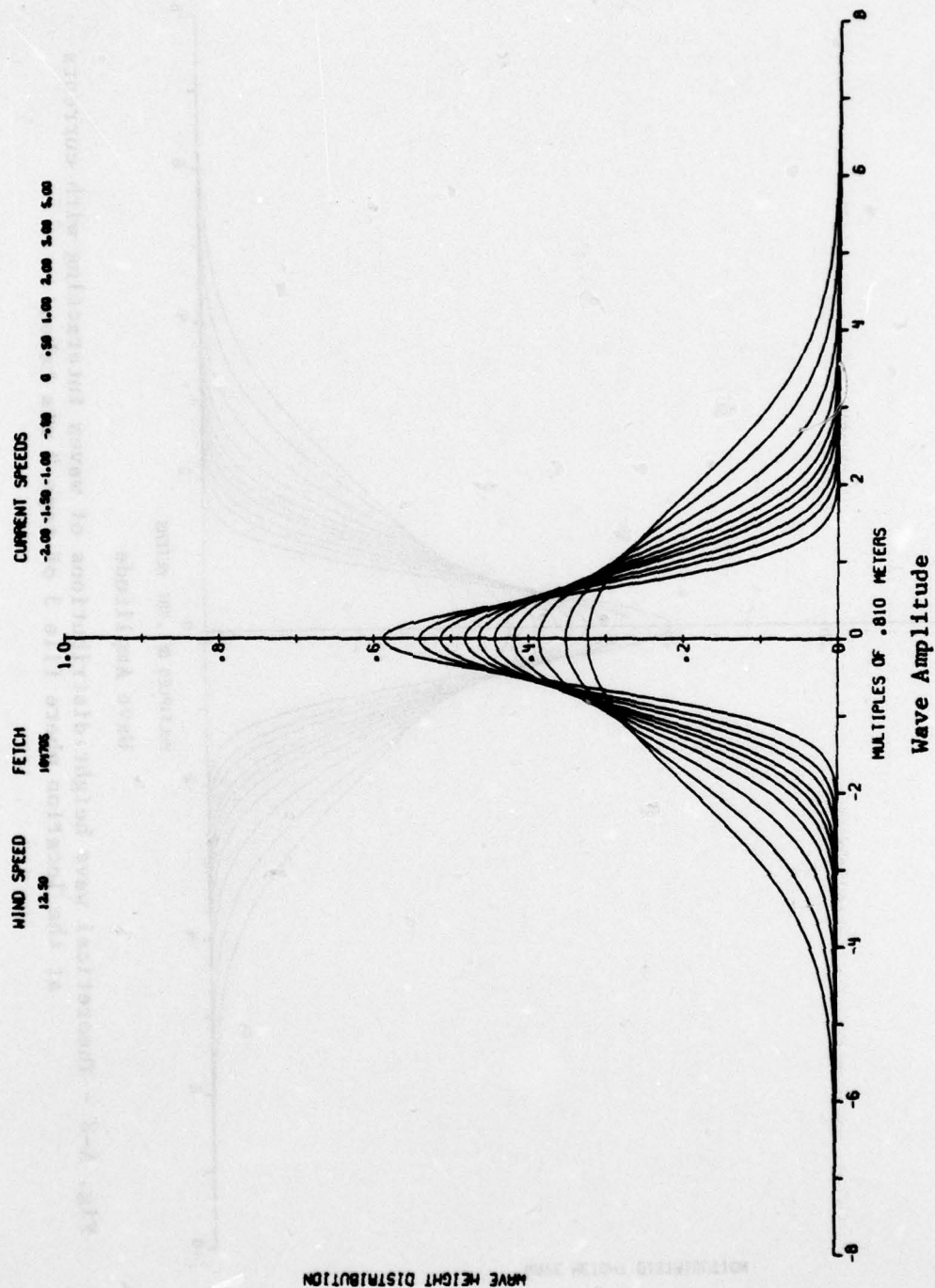


Fig. A-7 - Theoretical wave height distributions of waves interacting with currents at the location where file 2 of tape 2 was taken

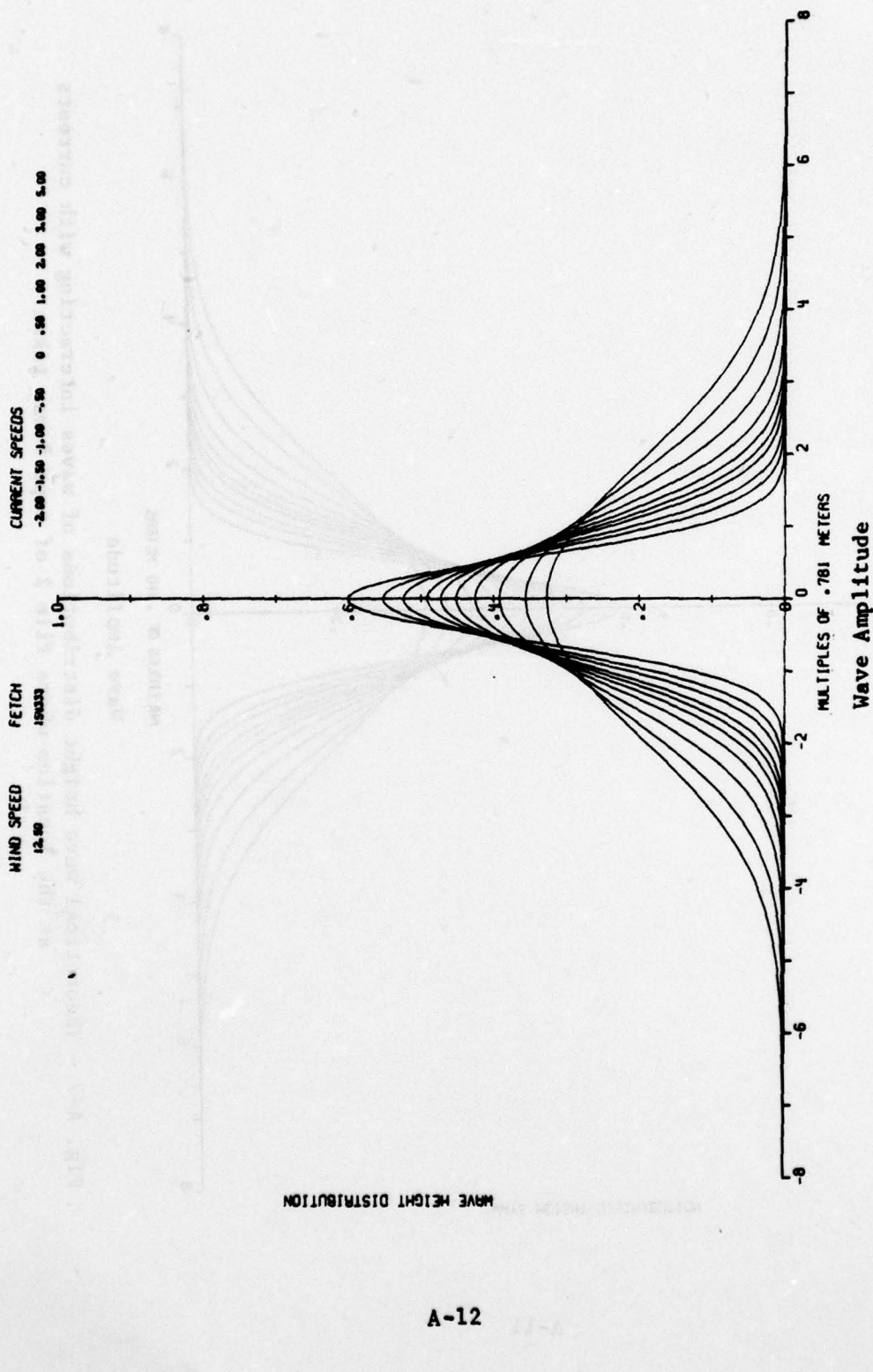


Fig. A-8 - Theoretical wave height distributions of waves interacting with currents at the location where file 3 of tape 2 was taken

APPENDIX B

COMPUTER PROGRAM

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PROGRAM HECK
BETA = EQUILIBRIUM COEFFICIENT
CUTP = CUT-OF WAVE FREQUENCY
DELTAN = INCREMENT FOR WAVE FREQUENCY
DELTA = DISTANCELESS FETCH PARAMETER
F(1,J) = JTH FETCH VALUE FOR 1 TH WIND SPEED
FREQ = TOTAL WAVE FREQUENCY
FREQM = PEAK WAVE FREQUENCY FOR FIXED WIND SPEED AND
        FETCH
GA = GRAVITATIONAL ACCELERATION
NF(1) = NUMBER OF FETCHES FOR EACH WIND SPEED
NLPHIC(1) = LIMIT OF THE NUMBER OF INTEGER INCREMENTS
        FOR PHIC(L,K)
NJ = NUMBER OF CURRENTS
NW = NUMBER OF WIND SPEEDS
NMF = NUMBER OF WAVE FREQUENCIES
NPHIC(L,K) = WAVE FREQUENCY SPECTRUM WITH THE INFLUENCE
        OF CURRENT, L TH CURRENT AND K TH WAVE
        FREQUENCY
PX(1) = X-ARRAY FOR PLOT
PY(1) = Y-ARRAY FOR PLOT
SIGMA(L) = STANDARD DEVIATION FOR WAVE ELEVATION FOR L
        TH CURRENT
SIGMA(ME) = STANDARD DEVIATION FOR WAVE ELEVATION FOR
        NO CURRENT
SIGNOT = STARTING VALUE FOR PX ARRAY
TITLE(1) = DESCRIPTION OF THE DATA CARDS
U(1) = CURRENTS
W(1) = WIND SPEEDS
X(1) = X-COORDINATE OF THE SYMBOLS FOR CURRENTS
Y(1) = Y-COORDINATE OF THE SYMBOLS FOR CURRENTS
COMMON W(1),NF(20),F(1,20),U(1,3),PHIC(1,3,1500),
        INLPHIC(1,3),SIGMA(1,3),X(1,3),Y(1,3),PX(32),PY(32),
        ZTITLE(10),PLX(32),PLY(32),PLZ(254),XS(13),YS(13)
INTRINSIC CONSTANTS
PAUSE 1
GA=9.8
GAP=GAB*2
GAB=7.3
ETA=0.07*2
ETAB=0.09*2
PAI=3.14159
TWOPAI = 2. *PAI
DELTAN=0.01
DELTDF = 0.05
CUTP=14.3
NMF=CUTP/DELTAN
TLOG=LOGF(10.0)
FNAX = 15.
FNAY = 10.
FNID = FNAX/2.
FNID = FNAX/2.
FNID = FNAX/2.
FNID = FNAX/2.
XLEFT = -1.5
XRIGHT = 1.5
YSTOP = 2.
        YSBOTTOM = -3.
        YSANUR = YSBOTTOM+TLOG
        ANUR = FPF(YSANUR)
        XSCALF = (XRIGHT-XLEFT)/FNAX
        YCALF = (YSTOP-YSBOTTOM)/FNAY
        XLEFT = -4.
        XRIGHT = 4.
        YSTOP = 1.
        XSCALE = (XRIGHT-XLEFT)/FDMAX
        YSCALE = YSTOP/FNAY
        CALL PLOTS(PLZ,254,3)
        CALL PLOT(1,2,5,-3)
        XSMOT=3.75
        XSMOT=3.75
        DO 10 I=1,13
        XSMOT=XSMOT+0.5
        XS(1)=XSMOT
        YS(1) = FNAY+0.2
10 CONTINUE
        XNOT=0.5
        DO 30 I=1,13
        XNOT=XNOT+0.5
        X(1)=XNOT
        Y(1) = FNAY+0.2
30 CONTINUE
        READ-IN INFORMATION
        PRINT 500
        READ 506, (TITLE(1),1,1,18)
        READ 501, NW,(W(1),1,1,NW)
        READ 506, (TITLF(1),1,1,18)
        READ 507, NF,(NF(1),1,1,NF)
        READ 506, (TITLF(1),1,1,18)
        DO 50 I = 1,NW
        NFN = NF(1)
        READ 507, (F(1,J),J=1,NFN)
50 CONTINUE
        DO 60 I = 1,NW
        PRINT 503, W(1)
        NFN = NF(1)
        PRINT 508, (F(1,J),J=1,NFN)
60 CONTINUE
        READ 506, (TITLE(1),1,1,18)
        READ 501, NU,(U(1),1,1,NU)
        PRINT 504
        W(1)=U(1)
        U(1)=0.00
        LOOP 450 - FOR DIFFERENT VALUES OF WIND SPEED
        DO 450 I = 1,NW
        FREQM1=21.99*GA/W(1)
        LOOP 440 - FOR DIFFERENT VALUES OF FETCH
        NFN=NF(1)
        DO 440 J = 1,NFN
        DFP=GA*F(1,J)/W2
        FREQM2=DFP*80.33
        FREQM=FREQM1/FDFOM2
        FREQM5=FREQM*2
        BETA1=DFP*0.22

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BETA2=0.4775/BETA1
LOOP 109 - FOR DIFFERENT VALUES OF TOTAL WAVE FREQUENCY.
FREQ=0. CUT-OFF WAVE FREQUENCY IS 14.30 RAD/SEC
CALCULATE WAVE FREQUENCY SPECTRUM WITHOUT THE
INFLUENCE OF CURRENT
PHI1=2*PI*FREQ
PHI2=PI*FREQ
PHI3=PI*FREQ
PHI4=PI*FREQ
PHI5=PI*FREQ
PHI6=PI*FREQ
PHI7=PI*FREQ
PHI8=PI*FREQ
PHI9=PI*FREQ
PHI10=PI*FREQ
PHI11=PI*FREQ
PHI12=PI*FREQ
PHI13=PI*FREQ
PHI14=PI*FREQ
PHI15=PI*FREQ
PHI16=PI*FREQ
PHI17=PI*FREQ
PHI18=PI*FREQ
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PHI20=PI*FREQ
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PHI23=PI*FREQ
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PHI366=PI*FREQ
PHI367=PI*FREQ
PHI368=PI*FREQ
PHI369=PI*FREQ
PHI370=PI*FREQ
PHI371=PI*FREQ
PHI372=PI*FREQ
PHI373=PI*FREQ
PHI374=PI*FREQ
PHI375=PI*
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118 LOG(WAVE SPECTRA) (90.0,0.18)
CALL SYMBOL (0.25,FMAX+0.5,0.14,10,MIND,SPEED,0.0,0.10)
CALL SYMBOL (2.0,FMAX+0.5,0.14,5,FETCH,0.0,0.5)
CALL SYMBOL (4.0,FMAX+0.5,0.14,14,CURRENT SPEEDS,
10.0,14)
CALL NUMBER (10.4,FMAX+0.2,0.10,0.10,0.0,0.4HF5,2)
FETCH (11,J)
CALL NUMBER (1.75,FMAX+0.2,0.10,0.10,FFTCM,0.0,0.4HF5,0)
ICOUNT = 0
XPU = XS(1)
YPU = YS(1)
XPU = U(1)
ALPU = ARSF (XPU)
TUPU = URU+ALPU
CALL NUMBER (XPU,YPU,0.10,URU,0.0,0.4HF5,2)
IF (TUPU) 190,190,230
190 DO 200 IP = 2,MLE
ICOUNT = ICOUNT+1
XPU=XS(IP)
YPU=YS(IP)
XPU=U(IP)
ALPU = ARSF (XPU)
TUPU = URU+ALPU
IF (TUPU) 195,195,210
195 CALL NUMBER (XPU,YPU,0.10,URU,0.0,0.4HF5,2)
200 CONTINUE
GO TO 255
210 URU = U(MLE)
CALL NUMBER (XPU,YPU,0.10,URU,0.0,0.4HF5,2)
DO 220 IC = 1,P+NU
ICP = IC+1
XPU = XS(ICP)
YPU = YS(ICP)
YPU = U(IC)
220 CALL NUMBER (XPU,YPU,0.10,URU,0.0,0.4HF5,2)
TO 295
230 DO 240 IP = 2,MLE
XPU = XS(IP)
YPU = YS(IP)
YPU = U(IP)
ALPU = ARSF (XPU)
TUPU = URU+ALPU
IF (TUPU) 250,250,235
235 CALL NUMBER (XPU,YPU,0.10,URU,0.0,0.4HF5,2)
240 CONTINUE
GO TO 295
250 URU = U(MLE)
CALL NUMBER (XPU,YPU,0.10,URU,0.0,0.4HF5,2)
DO 260 IC = 1,P+NU
ICP = IC+1
XPU = XS(ICP)
YPU = YS(ICP)
YPU = U(IC)
260 CALL NUMBER (XPU,YPU,0.10,URU,0.0,0.4HF5,2)
270 CONTINUE
270 VPL2=LOGF (YB,1)/TLOG-YBNOTM
CALL PLOT (XPL,YPL,3)
LOOP 280 - FOR SCALING AND PLOTTING
INDIC1=INDIC+1
DO 280 MM = 1,NPWF
FREQ=FREQ+DELTA
XPL1=LOGF (FREQ)/TLOG-XSLEFT
XPL = XPL1/XSCALE
YPL1=PHIC (M,MM)
CHECK=YPL1-ANUR
IF (CHECK) 260,260,270
280 CONTINUE
270 VPL2=LOGF (YB,1)/TLOG-YBNOTM
VPL = VPL2/YSCALE
CALL PLOT (XPL,YPL,3)
LOOP 290 - FOR SCALING AND PLOTTING
INDIC1=INDIC+1
DO 290 MM = 1,NPWF
FREQ=FREQ+DELTA
XPL1=LOGF (FREQ)/TLOG-XSLEFT
XPL = XPL1/XSCALE
YPL1=PHIC (M,MM)
CHECK=YPL1-ANUR
IF (CHECK) 290,290,270
290 CONTINUE
270 VPL2=LOGF (YB,1)/TLOG-YBNOTM
VPL = VPL2/YSCALE
CALL PLOT (XPL,YPL,2)
280 CONTINUE
290 CONTINUE
CALL PLOT (-XSLEFT,-15.0,-3)

INTEGRATION OF THE WAVE FREQUENCY SPECTRA FOR THE
STANDARD DEVIATION SIGMA FOR WAVE ELEVATION
LOOP 310 - FOR DIFFERENT VALUES OF CURRENT
DO 310 M = 1,MF
MMK=MLPHIC (M)
MMK=MMK+1
PHIC (M,MMK)=0.
LOOP 300 - INTEGRATION FOR FIXED VALUE OF CURRENT
SUM=0.
DO 300 MM = 2,MMK,2
MM1=MM-1
MM2=MM
MM3=MM+1
SUM=PHIC (M,MM1)+4.0*PHIC (M,MM2)+PHIC (M,MM3)
SUM=SUM+MMIND
300 CONTINUE
SIGMA1=SUMDELTA/3.
SIGMA=1+SORT (SIGMA1)
PRINT 505, W(11,F(11,J),U(11),SIGMA(M)
310 CONTINUE

PLOTS OF THE WAVE HEIGHT DISTRIBUTION FUNCTIONS
DESCRIPTIONS OF THE PLOTS

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**B-4**

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2F14.7)
406 FORMAT(18A4)
407 FORMAT(1A12.0)
408 FORMAT(12X.10(F7.0.2X)/12X.10(F7.0.2X))
409 FORMAT(1X.11HWIND SPEED=.FA.2.2X.6HFFTC=.F7.0.2X.
114HCHOPENT SPEED=.FA.2.2X.11HWAVE SPECTDUM)
410 FORMAT(2X.7(F14.7.2X))
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